

Final Report

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A Study of ice Accretion Physics to Improve the Ice Accretion on Airfoils"

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Introduction

This three-year grant began on November 7, 1996 and was no-cost extended to end on October 30, 2000. The objectives of the grant were: 1) To examine the effect of wind tunnel turbulence on ice accretion, 2) To determine the relationship between ice accretion geometry and airfoil performance, and 3) To determine if the wake-survey method was an appropriate experimental technique for iced-airfoil drag measurement. As specified in the grant the primary deliverables for this research were annual reports in the form of AIAA papers presented at national meetings each year. MS theses and annual oral reports to be given at NASA Lewis (now Glenn) were also deliverables. Six AIAA papers documented the research findings from this study (Refs. 1 - 6), Mr. Chad Henze's MS thesis describes the wind tunnel turbulence work in detail (Ref. 7), and a summary of the icing wind tunnel turbulence work was published in the archival AIAA Journal of Aircraft (Ref. 8). A brief summary of the findings is given below. Please refer to the reports for the details of the studies and findings.

Icing Wind Tunnel Turbulence

Current understanding of the ice accretion process is based largely on icing wind tunnel tests. Wind tunnel turbulence has been identified as having potentially important effects on the results of tests performed in icing tunnels. The turbulence intensity level in icing tunnels in the absence of the spray cloud had been previously measured and found to be quite high due to the lack of turbulence reducing screens, and to the presence of the spray system in the settling chamber. However, the turbulence intensity level in the presence of the spray cloud had not been measured. In this study, a method for making such measurements was developed and a limited set of turbulence measurements was taken in the NASA Lewis Icing Research Tunnel. Turbulent velocity fluctuations were measured using hot-wire sensors. Droplets striking the wire resulted in distinct spikes in the hot-wire voltage that were removed using a digital acceleration threshold filter. The remaining data were used to calculate the turbulence intensity. Using this method, the turbulence intensity level in the Icing Research Tunnel was found to be highly dependent

on nozzle air pressure, while other factors such as nozzle water pressure, droplet size, and cloud liquid water content had little effect.

From this study the following conclusions were drawn:

1. A hot-wire probe with a digital acceleration filter can be successfully used to measure the turbulence level in an icing tunnel with the water spray on.
2. The airfoil shield reduced the mass of water at the hot-wire sensor location by deflecting the large droplets. If such shielding is used, a small correction in the measured turbulence intensity must be applied due to the airfoil-generated turbulence.
3. The heated nozzle air used to prevent ice formation in the nozzles caused temperature fluctuations that were falsely interpreted as velocity fluctuations. Turbulence data must be corrected to account for this effect unless measurements can be made with the nozzle air at the freestream temperature.
4. At a given velocity, the measured turbulence intensity in the icing tunnel spray cloud was primarily a function of nozzle air pressure. Nozzle water pressure had only a small effect on the turbulence level. Changes in turbulence level due to LWC and droplet size can be explained in terms of the nozzle air pressure. Turbulence measured in the icing cloud was consistently slightly higher than that measured with no water present at the same nozzle air pressure. However, it is not clear at this time whether this is due to the presence of the droplets, or due to small droplets striking the wire that were not properly removed by the threshold filter.

This study was successful in developing the experimental techniques. However, a more thorough study of the turbulence level in the Icing Research Tunnel and other icing tunnels needs to be performed. These techniques may also be useful in measuring the turbulence levels in natural icing clouds during flight test. Once turbulence levels in icing tunnels and natural icing clouds are known, progress can be made in understanding the influence of tunnel turbulence on the ability of the tunnel to simulate the natural icing environment.

Ice Accretion Geometry and Airfoil Performance

A systematic study of the effect of simulated ice shape geometry on airfoil aerodynamics was performed. A wind tunnel test was performed in the UIUC tunnel using a flapped NLF(1)-0414 airfoil (borrowed from the AGATE program) where aerodynamic parameters including hinge moment were measured. The ice shapes tested were based on IRT measurements and designed to simulate a single glaze ice horn with leading-edge radius, size and airfoil surface location varied. All nine ice simulations were tested at six different leading-edge locations. The objective of this research was to determine the sensitivity of iced airfoil aerodynamics to ice shape geometry. Configurations were also tested at three different Reynolds numbers (0.5, 1.0, and 1.8×10^6). It was determined that ice horn leading-edge radius had only a small effect on airfoil aerodynamics. However, the aerodynamic performance was very sensitive to ice shape size and location. An almost linear relationship between loss in maximum lift and ice horn location was found with the largest loss at the furthest location back on the upper surface. Reynolds number

was found to have little effect on the aerodynamic results on the airfoil with simulated ice shapes.

The results to date indicate that ice surface location combined with ice horn height play a crucial role in determining iced airfoil performance degradation. It also seems that the size of the ice accretion, even when sufficiently large, does not alone determine the "critical" ice shape. Specific conclusions are:

1. Simulated ice shape size and location had a significant effect on the measured reduction of $C_{l_{max}}$ and other measures of aerodynamic performance.
2. The relationship between surface location and $C_{l_{max}}$ near the leading edge ($x/c < 3.5\%$) is fairly linear with $\Delta C_{l_{max}}$ increasing as the ice shape is placed further aft on the airfoil upper surface.
3. $C_{l_{max}}$ dependence on ice simulation height and radius was a minimum at $s/c = 0.4\%$
4. Reynolds Number had little effect on the $C_{l_{max}}$ of the airfoil with simulated ice.
5. Radius effects are largest for large horns at large s/c locations but are small compared to size and location effects.
6. Drag results seem to support the idea that iced airfoil drag is lowest at the angle of attack the ice was accreted at (α_{iced}).
7. Drag results also suggest that $s/c = 3.4\%$ may represent the aft limit of what can be categorized as a "leading-edge" ice.

Wake Survey Techniques for Iced Airfoils

The drag coefficient of an airfoil with an ice accretion is measured in the IRT, UIUC tunnel, and most other facilities using the wake survey method. However, wake survey methods are known have fundamental errors when the flow in the wake has 3-D, unsteady flow at large flow angles. It was anticipated that this was the case in iced airfoil wakes. The goal of this research is then is to understand these fundamental deficiencies of the wake survey method, evaluate the resulting errors in C_d measurement, and propose ways to improve the technique if warranted.

Research was therefore undertaken to study of the wake survey method for drag measurement for bodies with large unsteady separated wakes. The intended application was airfoil testing with simulated ice accretions. Detailed surveys of the wakes of an S809 18"-chord airfoil, with and without simulated ice, and a 1" diameter cylinder were acquired. In the investigation, a 7-hole probe, a Pitot total-pressure probe, a \cos^2 probe, and a single element hot-wire probe were used to measure total and static pressures, all three components of wake velocity and the turbulence intensity. The effect of the type of probe on the pressure measurement in the turbulent flow was analyzed. The Jones' formula and van Dam's equation, which includes the effect of the Reynolds stress, were used in the calculation of the profile drag coefficient. The results showed a significant effect of wake turbulence on the pressure probe measurements and the calculated drag coefficient when the turbulence intensity was greater than 8 percent. The drag coefficient results from the 3 different probes and the two wake drag equations could be brought into reasonable agreement by correcting the data based on the measured wake turbulence.

Based on this research, the following conclusions can be made:

1. The cylinder and iced airfoil wakes were highly turbulent and affected the measured wake total pressures from the 3 probes according to the probe tip geometry.
2. The measured wake streamwise total pressures from the three probes used could be brought into good agreement by knowing the probe turbulence characteristics and the three turbulence components.
3. The cylinder drag coefficient could be measured to within 5% of the assumed correct value using the corrected total pressures and the simplified Jones equation or the van Dam equation, which included the turbulent Reynolds stress term.
4. Flow angles in the wake were low (< 3 degrees) and for the iced airfoil where maximum lift is low the flow angle can be ignored.
5. An accurate drag coefficient for an iced airfoil should be obtainable from the wake survey method using simple probes for total pressure and wake turbulence measurement and standard momentum integral equations.
6. More research is needed in iced airfoil wakes to understand the turbulence field to enable the total pressure measurements to be accurately corrected.
7. Further validation of the iced airfoil case is required, but results from this study are very encouraging.

This research has been continued under a new NASA grant (NCC 3-852). As a result of the initial work under the original grant items 6 and 7 above have been addressed. This work is planned to be presented at the AIAA Applied Aerodynamics meeting in June 2002.

References

- ¹ Bragg, M.B., Lee, S. and Henze, C.M., "Heat-Transfer and Freestream Turbulence Measurements for Improvement of the Ice Accretion Physical Model," AIAA Paper No. 97-0053, Reno, NV, January 6-9, 1997.
- ² Henze, C.M., Bragg, M.B. and Kim, H.S., "Freestream Turbulence Measurements in Icing Conditions," AIAA Paper No. 98-0096, Reno, NV, January 12-15, 1998.
- ³ Kim, H.S. and Bragg, M.B. "Effects of Leading-Edge Ice Accretion Geometry on Airfoil Aerodynamics," AIAA Paper No. 99-3150, Proceeding of the 17th AIAA Applied Aerodynamics Meeting, Norfolk, June 28 – July 1, 1999, pp. 379 - 391.
- ⁴ Lee, S., Kim, H. and Bragg, M.B., "Investigation of Factors that Influence Iced-Airfoil Aerodynamics," AIAA Paper No. 2000-0099, Reno, NV, Jan. 10-14, 2000.
- ⁵ Lu, B. and Bragg, M.B., "Experimental Investigation of Airfoil Drag Measurement With Simulated Leading-Edge Ice Using the Wake Survey Method," Paper No. 2000-

3919, Proceeding of the 18th AIAA Applied Aerodynamics Conference, Denver, August 14-17, 2000, pp. 12-21.

- ⁶ Lee, S. and Bragg, M.B., "The Effect of Ridge-Ice Location and the Role of Airfoil Geometry," AIAA Paper 2001-2481, Proceeding of the 19th AIAA Applied Aerodynamics Conference, Anaheim, CA, June 11-14, 2001
- ⁷ Henze, C.M., "Turbulence Intensity Measurements in Icing Cloud Conditions," M.S. thesis, University of Illinois at Urbana-Champaign, Jan. 1997.
- ⁸ Henze, C.M. and Bragg, M.B., "Turbulence Intensity Measurement Technique for Use in a Icing Wind Tunnel," *Journal of Aircraft*, No. 3, 1999, pp. 577-583.